

Microlensing of tidal debris on the Magellanic great circle

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ABSTRACT

Increasing evidences suggest that the Galactic halo is lumpy on kpc scales due to the accretion of at least a dozen small galaxies (LMC/SMC, Sgr, Fornax etc.). Faint stars in such lumpy structures can significant microlense a background star with an optical depth $10^{-7} - 10^{-6}$, which is comparable to the observed value to the LMC (Alcock et al. 1996c). The observed several microlensing events towards the LMC can be explained by a tidal debris tail lying in the Magellanic plane if the progenitor of the Magellanic Clouds and Stream and other satellite galaxies in the Magellanic plane has a mass about twice that of the disc of the LMC. The LMC stars can either lense stars in the debris tail behind the LMC, or be lensed by stars in the part of debris tail in front of the LMC. The models are consistent with an elementary particle dominated Galactic halo without massive compact halo objects (MACHOs). They also differ from Sahu's (1994) LMC-self-lensing model by predicting a higher optical depth and event rate and less concentration of events to the LMC center.

Key words: Magellanic clouds - gravitational lensing - dark matter - Galaxy : halo - galaxies : individual (Sgr) -dwarf galaxies

1 INTRODUCTION

Nearly twenty years ago Searle and Zinn (1978) proposed, on the basis of the spread of horizontal branch morphology of globular clusters and the lack of a metallicity gradient in the Galactic halo, that the Galactic halo forms by gradual merging of many infalling sub-Galactic lumps. The well-known Magellanic Stream (Mathewson, et al. 1974) and the newly discovered galaxy in the Sagittarius constellation (Ibata, Gilmore and Irwin 1994) are the two most impressive signatures printed by on-going infalls. The former is a long ribbon of neutral gas starting from the direction of the Magellanic Clouds, across the south Galactic pole, occupying $10^\circ \times 100^\circ$ of the sky. The latter is a faint comoving group of stars in a $5^\circ \times 20^\circ$ strip towards the Galactic center. If the halo of the Galaxy extends well beyond the LMC and the SMC, then it would also contain eight other low luminosity and low surface brightness satellite galaxies (dwarf galaxies) (Irwin and Hatzidimitriou 1995 and references therein).

Current understanding of the formation of Milky Way size halos based on collisionless cosmological simulations is that they form with continuous accretion of numerous smaller halos (White 1996). On the order of $\sim 10^{10} M_\odot$ material can be accreted by dynamical friction with a steady state dark halo (Tremaine 1980, Tóth and Ostriker 1992)

even after an initial violent merger phase (Toomre and Toomre 1972). Material from a minor infall will be confined close to a specific orbit of a fixed potential. For an accreted lump on an orbit with a small peri-galactic radius (within 20 kpc), the tidal force of the Galaxy becomes strong enough to liberate material from the lump (Quinn and Goodman 1986, Quinn, Hernquist, Fullagar 1993). The marginally bound fraction of a small galaxy is peeled off with each peri-centric passage, and is sent on a gradual leading/trailing drift nearly along the orbit according to the initial peculiar velocity (Oh, Lin & Aarseth, 1995, Johnston, Hernquist & Bolte 1996). The tails generally trace great circles around the host galaxy for nearly spherical potential in the halo (Lynden-Bell & Lynden-Bell 1995), and the tails grow with a rate proportional to the lump's initial velocity dispersion (Johnston et al. 1996).

Observations on the intrinsic number density of dwarf galaxies in our halo can set a limit on hierarchical formation models. The recent discovery of Sgr has spurred systematic searches for other predicted small galaxies accreted by the Galaxy in the past one Hubble time (Johnston et al. 1996, Lynden-Bell and Lynden-Bell 1995, Mateo 1996). Large tidal tails are generally low surface brightness, kinematically cold, great circle like moving groups, whose coherent structures are traceable with halo globular clusters, luminous horizontal branch stars, giant branch stars or planetary nebulae. An ideal survey should combine photometry, radial velocities

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and proper motions of bright objects in a large fraction of the sky. In the past dwarf galaxies are mainly found in line of sight directions which have been frequently studied for other interesting astronomical objects, e.g., peculiar stars, halo globular clusters. This biases against those in “empty” or “boring” line of sight directions. The low surface brightness of dwarf galaxies also makes it more challenging to detect in line of sight where there are high surface brightness extended objects, e.g., the Galactic bulge and the Magellanic Clouds. The eight known dwarf galaxies and the late serendipitously discovered Sgr dwarf galaxy show perhaps more of the need for optimized survey in the past (ideally a photometric and kinematic survey of luminous tracers of a large fraction of the sky) than the intrinsic rareness of these faint structures. The Sgr, which is about 1/3 the distance to the SMC with a comparable total mass at the high end of current estimate $10^{8-9} M_{\odot}$ (Ibata, Gilmore, Wyse, & Suntzeff 1997), has evaded previous frequent studies of the same low-extinction Galactic bulge region of the sky, and was found as soon as a kinematic survey of K-giants at high bulge fields was completed (Ibata et al. 1995).

Current microlensing surveys to the Galactic bulge and towards the Magellanic Clouds offer good possibility to detect such debris; stars in the debris are detectable as lenses, amplified sources or bright variables. In fact a relative faint part of the Sgr galaxy, which is roughly behind the Galactic center, was first seen in RR Lyraes in the microlensing surveys to the bulge (Alard 1996). A star in Sgr has also a very high chance being lensed by the stars in the Galactic bulge and disc, which might be detectable despite the low density of the sources. As for surveys towards the Large Magellanic Cloud, 5-8 microlensing events of possibly LMC sources are observed (Alcock 1996c). However, possibility of lensing by tidal debris has not been studied. The conventional interpretation involves a mathematically smooth r^{-2} power-law dark halo made of a mixture of massive compact halo objects (MACHOs) and weakly interacting massive particles (WIMPs); the MACHO collaboration favors a Galactic isothermal dark halo with about half of the dynamical mass $2^{+1.2}_{-0.7} \times 10^{11} M_{\odot}$ out to the distance of the LMC (50 kpc) in $0.5^{+0.3}_{-0.2} M_{\odot}$ white dwarf (WD) mass objects and the rest in distributed form (Alcock et al. 1996a,c and references therein). Clearly these conclusions hinge on cosmological bases for a smooth r^{-2} dark halo and the dichotomy of the dark mass (why either WIMPs or WDs?) in the halo. Explaining the shortage of lensing events simply by a (universal?) MACHO-to-WIMP ratio has the potential problem of trivializing the (possibly complex) structure in the halo which we know very little. Also crucial is a proper estimation of background non-MACHO events, for example, events due to stellar lenses in the LMC’s bar (Sahu 1994, Bennett et al 1996), and stellar lenses in clumpy structures in the halo, ranging from globular cluster to dwarf galaxy sized clumps (Maoz 1994, Metcalf and Silk 1996, Zhao 1996).

In this paper, I show that gravitational microlensing surveys have the potential of detecting tidal tails in the halo with sizes ranging from the Sgr to the Magellanic Stream. In particular I make the possible connection between hierarchical formation scenario and microlensing events observed towards the LMC from ongoing experiment of MACHO collaboration. If a small fraction (1/10) of the Galactic halo’s mass inside 16 kpc (the Sgr’s distance from the Galactic

center) were accreted from late infall of 10^2 Sgr size objects each with a sky angular covering factor 0.25%, then there is a significant probability $\sim 25\%$ of having one towards the LMC, SMC or any other line of sight. In reality the amount of late infall might be limited, at least at small radii, because high proper motion local halo sample shows only a weak tail of stars bluer than the bulk of the stellar halo with $B - V \sim (0.4 - 1)$ (Unavane, Wyse, & Gilmore 1996). Nevertheless tidal material surrounding the Magellanic Clouds, and/or any tidal debris lying on the great circle drawn by the Magellanic Stream, Ursa Minor and Draco, would be consistent with the merging of the Magellanic Clouds with the Galaxy (Kunkel 1979, Lynden-Bell 1976, 1982). §2 estimate the lensing probability (optical depth) towards the Magellanic Clouds in two configurations of tidal debris: a uniform grand tidal tail and a short Sgr-like tidal tail on the Magellanic great circle. §3 considers the case that tidal debris is surrounding the LMC. §4 calculates the event time scales and lens mass function. §5 compares several interpretations of the observed events towards the LMC. §6 discusses search techniques.

2 LENSING BY TIDAL DEBRIS ON THE MAGELLANIC GREAT CIRCLE

2.1 Evidences for tidal debris

A yet-to-be-detected strip of faint stars around the Magellanic great circle has long been predicted in merger models where an ancient gas-rich lump, supposedly the progenitor of LMC and SMC, was captured and torn apart by tidal force of the Galaxy (Lynden-Bell 1976, Kunkel and Demers 1977). As the lump spirals down the halo of the Galaxy due to dynamical friction on a massive lump (Tremaine 1976), the increasing tidal force of the Galaxy, together with a possibly recent close encounter of the SMC with the LMC, and the ram stripping in the halo, liberates stars as well as gas from the lump during its last 1-6 orbits. This merging event might have created several structures which we now see in the vicinity of the Magellanic great circle: the 100° long Magellanic Stream (Lin and Lynden-Bell 1982, Murai and Fujimoto 1980, Lin, Jones, & Klemola 1995 and references therein), the irregular Large Cloud, the strongly prolate Small Cloud (Caldwell & Coulsin 1986), the inter-Cloud Bridge with distinct gas lumps (McGee & Newton 1986) and stellar associations (Grondin, Demers & Kunkel 1992) and eight known dwarf spheroids scattered on the Magellanic great circle (Lynden-Bell 1976) or nearby planes (Kunkel 1979, Lynden-Bell 1982, Lynden-Bell and Lynden-Bell 1995). Early radial velocity data of the tracers, including a number of globular clusters and high velocity clouds compiled in Kunkel (1979), also support this explanation. A polar orbit would also account for the nearly polar elongation of the Ursa Minor and Draco galaxies and their surrounding high velocity clouds; that they are at the almost opposite direction of the Magellanic Clouds might be an example of a stable collinear three-body systems in an extended halo (Hunter and Tremaine 1977). It is possible that these two dwarf galaxies are separated from the Clouds much early on. The material now in the inter-Cloud Bridge and the Magellanic Stream might be mostly due to a recent encounter of the Clouds.

The Magellanic Clouds should be shrouded with a faint inhomogeneous band of liberated material, gas or stars as a result of the merger event which dynamically links together several known structures on the Magellanic great circle. Numerical simulations shows such a situation would be very natural; for example, the tidal material between 30-70 kpc in Fig.11 of Gardiner et al. (1994), sandwiching the Large Cloud. Observationally the surrounding debris is perhaps manifested by the gas (McGee & Newton 1986) and star clusters (Irwin 1991 and references therein) bridging the Large Cloud and the Small Cloud. Some five stellar associations in the region also show a distance spread as much as 17 kpc (Grondin, Demers & Kunkel 1992). The huge depth of the SMC (~ 10 kpc) is also suggestive of a recent encounter with the LMC; see the comparison of SMC Cepheid distances (Caldwell & Coulson 1986) with simulation in Fig.13 of Gardiner et al. (1994).

As long as the above picture is qualitatively correct, it is inevitable that stars in the surrounding debris will have a fair chance to microlense or be microlensed by stars in the LMC and SMC, contributing a few events in the current microlensing surveys towards the Magellanic Clouds.

Have past observations of the LMC pretty much ruled out any large moving group right in front of the LMC? Probably not, if the two differ in distance modulus by only 0.5 to 0.9 magnitude (corresponding to the foreground material at about 4/5 to 2/3 of the distance to the LMC), and if the contrast in the column density between the low surface brightness lump and the LMC is around 100. The Sgr dwarf, for example, has a density about 1 per square arcmin for horizontal branch stars (Ibata et al. 1995), which is roughly 3% of the density of bulge stars at the same field (Alard 1996, Alcock et al. 1996b). A CCD observation of a field with one sq. armin area of the LMC might yield an overlapping CM diagram of 10^4 stars from the LMC and 10^2 stars from the foreground material, both of mixed stellar populations due to strong age and metallicity spread. The half a magnitude difference and the weak contrast might be considered insignificant given internal extinction of the LMC (can be as much as 1.5 mag. at the LMC bar, Sahu 1994 and references therein) and small number statistics. The low contrast, the faintness, the large size, and the very irregular morphology of the LMC also conspire to make detection of any tidal tails in small degree size photographic plates of the LMC difficult. The Sgr horizontal branch stars are spread out over many degrees of the sky with a density about 1 per square arcmin and ~ 19 magnitude in V . Stellar populations of the Galactic bulge have been studied for 50 years since Baade's (1946) pioneering discovery of variable stars in the direction, the recently found Sgr shows the limitations of previous observations.

It is highly promising to search for RR Lyraes, and other variable populations of the debris in the variable star catalogues of current microlensing surveys. A weak indication of foreground material is already seen in earlier surveys of variable stars of the region. Payne-Gaposchkin (1971) published a survey of variable stars in the direction of the LMC, listing 29 short-period variables as foreground RR Lyraes with distances between 5 and 25 kpc. Interestingly 9 of these cluster at a narrow distance modulus range 16 – 17 mag, which corresponds to a line-of-sight distance about 16 to 25 kpc. The follow-up photometric and spectroscopic studies

by Connolly (1985) and Smith (1985) confirmed that most of these short-period variables are indeed foreground metal poor RR Lyraes with a radial velocity different from LMC RR Lyraes. Since only about 1 RR Lyrae between 5 to 16 kpc, and also between 16 to 25 kpc towards the LMC are expected from a smooth $r^{-3.5}$ or r^{-4} density law for the RR Lyraes in the stellar halo (Saha 1985), the 9 RR Lyraes with distance modulus 16 – 17 mag. seem to trace a local over-density region.

Given the above lines of evidence for tidal debris and the important implications on the nature of the dark matter, it becomes highly interesting to examine the lensing optical depth of the debris in some detail.

2.2 Observed optical depth to the LMC

The observed optical depth to the LMC is still uncertain. The number of claimed microlensing events from the MACHO and EROS experiments has been fluctuating between 1 to half a dozen. Based on 5-8 events which pass their recent selection criteria the MACHO team estimated an optical depth towards the LMC

$$\tau_{obs} = 0.17_{-0.05}^{+0.09} \times 10^{-6}; \quad (1)$$

a somewhat higher value is also given in a more recent estimation (Alcock et al. 1996c).

2.3 Optical depth and the mass of a grand Magellanic tidal tail

Theoretically it is still premature to predict a precise range of microlensing optical depth accountable by the debris of the old Magellanic system without a detailed N-body modeling of the morphology and the clumpyness of the tail and the total mass of the system. Nevertheless some insights to the problem can be obtained for some greatly simplified cases. The morphologies which I will assign to the debris tail should be treated as toy models only. They clearly cannot match the variety and complexity of tidal tails frequently seen in mergers and N-body simulations (e.g. Toomre & Toomre 1972).

This section deals with a grand *uniform* tidal tail due to a galaxy slightly more massive than the Magellanic Clouds. The clumpyness of the grand tidal tail is modelled in §3 by *adding* a small kpc size tidal tail of a disrupted dwarf galaxy on top of the uniform grand tidal tail. In both cases only debris in the front side of the LMC is considered. The consequences of tidal debris surrounding the LMC or *behind* the LMC are studied in §4.

It is well-known that the optical depth towards a source at distance D_s is given by (Paczynski 1986)

$$\tau = \frac{4\pi G}{c^2} D\Sigma = \frac{4\pi G}{c^2} \int_0^{D_s} (1-x) D_l \rho(D_l) dD_l, \quad x \equiv \frac{D_l}{D_s}, \quad (2)$$

where

$$D \equiv D_s x(1-x) \quad (3)$$

and $\rho(D_l)$ are the effective distance and the density of the lens at distance D_l , Σ is the surface density of lenses. So the lensing optical depth by the debris tail depends on geometry

of our line of sight to the LMC with the debris plane, and the density distribution along the tail.

As an order of magnitude estimation, it is reasonable to assume the debris tail has a uniform torus with a cross section πb^2 , a length L , a total mass M , and a uniform density $\rho = \frac{M}{\pi b^2 L}$. This picture is motivated by N-body simulations of accretion of a dwarf galaxy, where the dwarf galaxy is shown to be disrupted into a ring like distribution (Quinn and Goodman 1986, Quinn, Hernquist, Fullagar 1993). Assume that the Sun is sufficiently close to the Galactic center, so that our line of sight to the LMC is parallel to the debris plane, and in fact, inside the debris central plane within $\pm b$. For the time being assume the debris tail is sufficiently wrapped around the sky, so that the optical depth is nearly the same around all line-of-sight directions within $\pm b$ of the central plane of the debris. Take the average of these line of sight directions, I have

$$\langle \tau \rangle \approx \frac{4\pi G}{c^2} \int_{-b}^b \frac{dz}{2b} \int_{-\pi}^{\pi} \frac{d\theta}{2\pi} \int_0^{D_s} dD_l D_l \rho(D_l) \quad (4)$$

$$= \frac{GM}{c^2 b}, \quad M = \int dr^3 \rho \quad (5)$$

where I have made the approximation that $(1 - x) \approx 1$ in eq. 2.

More generally, I find

$$\tau = \frac{GM}{c^2 b} \xi = 0.17 \times 10^{-6} \frac{M}{1.5 \times 10^{10} M_{\odot}} \frac{8 \text{ kpc}}{2b} \xi, \quad (6)$$

where ξ is a dimensionless quantity of order unity, which takes into account of the $(1 - x)$ factor, and the fact that the optical depth can be a strong function of directions for a short debris tail which wraps around the sky only once or less.

For the validity of the plane parallel approximation, the thickness of the debris plane, $2b$, must be at least comparable to the Sun's distance from the Galactic center R_0 , so $2b \geq R_0 = 8 \text{ kpc}$, which translates to about 9° at the LMC's distance. This is consistent with the width of the Magellanic Stream $\sim 10^\circ$. The luminous disc of the LMC has a mass of about $10^{10} M_{\odot}$. So eq. 6 and 1 together imply that *a low surface brightness debris tail with mass in stellar objects comparable to the disc of the LMC is needed to explain the observed microlensing optical depth*. If the ancient Magellanic system (Lynden-Bell 1976, Kunkel and Demers 1977) has the combined mass of the debris inferred here, the Magellanic Clouds, and several satellite galaxies and high velocity clouds on nearby great circles, I estimate its dynamical mass between $(2 - 4) \times 10^{10} M_{\odot}$.

A lump with mass about twice that of the Magellanic Clouds would reduce its orbital radius (with same eccentricity) by half in half a Hubble time due to dynamical friction with an extended halo of the Galaxy (Tremaine 1976, Murray and Fujimoto 1980); the de-acceleration is proportional to the satellite's mass. A possible scenario for the structures around the Magellanic great circle is that the ancient Magellanic system on a polar eccentric orbit was probably disrupted during the first pericenter passages around 50 kpc to liberate some low mass dwarf galaxies such as Ursa Minor and Draco from the binary Magellanic Clouds. The later continues its doomed course deeper in the halo because of still strong dynamical friction. The SMC was disrupted by a perhaps recent close approach to the LMC, and the material

is then liberated by the halo tidal force to form the inter-Cloud Bridge and the giant Magellanic Stream (Gardiner et al. 1994, 1996). Ram pressure stripping due to a possible extended gaseous halo may have also played a role for the Stream (Moore & Davis 1994).

The above optical depth estimation applies also to a *localized debris distribution surrounding the LMC*, such as the inter-Cloud Bridge, perhaps as a result of the tidal shock in LMC's recent close encounter with the SMC. For simplicity, one might model the debris as a faint prolate-shaped distribution pointing in the direction of the LMC's space velocity. In this case, the ξ factor in eq. 6 is reduced by a factor $(1 - x) \sim \frac{b}{D_s}$ because the lens and the source are very close, but is enhanced by a factor $\frac{2\pi D_s}{b}$ because lensing is concentrated to a small angular region of the sky. So the two effects balance out, and ξ is still of order unity. Again debris of the mass of the order $10^{10} M_{\odot}$ is necessary; the exact result depends on the axis ratio and the angle of the prolate-shaped distribution with our line of sight, similar to the self-lensing of the Galactic bar (Zhao and Mao 1996).

If the debris tail is both short and far from the LMC, then the optical depth gains by a factor $\xi \sim \frac{2\pi D_s}{b}$. In this case a tidal tail with mass $10^{8-9} M_{\odot}$ is enough to explain the observed optical depth.

2.4 Optical depth of faint stars in a Sgr size galaxy

The calculation of the previous section assumes a homogeneous tidal tail on the Magellanic great circle, while a lumpy distribution is more plausible. If the ancient Magellanic lump had a few dwarf galaxies, those less dense than Ursa Minor and Draco might have been disintegrated into small tidal debris tails at their peri-galactic passes. The most efficient way to produce microlensing towards the LMC is to have one of these small tidal tails right in front of the LMC. Although fairly contrived, this particular model has a few easy to test predictions.

Let us estimate the microlensing optical depth due to lenses in a Sgr-like dwarf galaxy. The formalism is the same as used in deriving the optical depth of the dark halo (Paczynski 1986) except that the situation here is simpler since all the lenses are at nearly the same distance. Lacking the knowledge of the real distribution of these dwarf galaxies, I will simply "move" the Sgr dwarf galaxy in front of the LMC, and compute the microlensing probability of source stars in the LMC.

For the lenses in the dwarf galaxy between us and the LMC, the optical depth is (cf. 2)

$$\tau_{dg} = 0.17 \times 10^{-6} \frac{\Sigma}{20 M_{\odot} \text{pc}^{-2}} \frac{D}{12 \text{ kpc}}, \quad (7)$$

where I have scaled the physical quantities with characteristic values.

Σ is related to the surface brightness μ by $\Sigma = \Upsilon \mu$, where Υ is the mass-to-light ratio, but more precisely, the ratio of total mass in stars and other compact objects of the dwarf galaxy to the total stellar light of the dwarf galaxy. For the Sgr, the surface brightness of the dwarf galaxy (μ) is $4 L_{\odot} \text{pc}^{-2}$ near the nucleus and is decreased to about $1.5 L_{\odot} \text{pc}^{-2}$ at 10° from the nucleus (Ibata et al. 1995, Mateo et al. 1995, 1996). Dwarf galaxies are generally dominated

by dark matter from the core to the tidal radius with the total mass to total light ratio M/L probably in the range $5 - 200 M_\odot L_\odot^{-1}$ (Irwin and Hatzidimitriou 1995). Ibata et al. (1997) estimate that $M/L \sim 100 M_\odot L_\odot^{-1}$ for the Sgr. To make a conservative estimation for the lensing optical depth, I assume $\Upsilon = 10 M_\odot L_\odot^{-1}$, which is reasonable for an old population. This way the dwarf is dominated by a non-baryonic halo, and only a small fraction of the dynamical mass is in faint stars, which can lense.

The distance to the Sgr dwarf galaxy (D_d) is about $\frac{1}{2}$ of the distance to the LMC (D_s), so $D_s \approx 2D_d \approx 50$ kpc, and $D \approx 12$ kpc. Assume $\Upsilon \approx 10 M_\odot L_\odot^{-1}$, and $\mu = (1.5 - 4) L_\odot \text{pc}^{-2}$. I find the optical depth

$$\tau_{dg} = \left(\frac{\mu}{2L_\odot \text{pc}^{-2}} \right) \tau_{obs} = (0.8 - 2) \times \tau_{obs}, \quad (8)$$

is comparable to the observed value to the LMC τ_{obs} as given in eq. 1.

This conclusion is insensitive to the exact value of the dwarf's distance, because

$$\tau_{dg} \propto D \propto x(1-x), \quad x = \frac{D_d}{D_s}, \quad (9)$$

so τ_{dg} has a very broad peak at $x = 1/2$. Compared to the optimal half-way position which is adopted in eq. 8, the optical depth reduces only by 11% if the dwarf galaxy is at $2/3$ or $1/3$ of our distance to the LMC, by 25% at $3/4$ or $1/4$, and by 36% at $4/5$ or $1/5$. In the case that the tidal material is within 5 kpc to the LMC, the debris will be mixed with the material surrounding the LMC.

The optical depth is also insensitive to a small misalignment of the dwarf nucleus with the LMC. The Sgr has a very shallow major axis gradient of the surface brightness: I estimate an e-folding angular size from the nucleus about 10° . A tidal tail with such size is big enough to “cover” the sky area of the LMC.

Nevertheless it is unlikely for a Sgr-like tidal tail to cover both the LMC and the SMC, which are spaced more than twenty degrees apart. A comparable lensing optical depth to both the LMC and the SMC could rule out such a small tidal tail. By the same line of argument, a high lensing rate to the Andromeda galaxy, which is off the Magellanic great circle, would lend support to the explanation of the LMC events being due to a smooth distribution of MACHOs rather than a massive grand tidal tail on the Magellanic great circle. On the other hand, any sharp gradient of the event rate across the solid angle of the Andromeda galaxy would be indications for clumpiness in its own halo.

3 STARS ON TIDAL DEBRIS AS SOURCES FOR LENSING

Stars in the debris can also be sources for lensing. If the Magellanic Clouds are shrouded with tidal debris, then stars of the Clouds can also lense those in the background tidal debris. It is the opposite situation compared to the situation where foreground debris stars lense background Magellanic Cloud stars, and has the advantage of hiding the debris easily. Both are very different from Sahu's suggestion of LMC self-lensing, as the debris can be quite a distance (several kpc) in front or behind the LMC, so the lensing optical depth

can be much higher; the depth of the disturbed SMC and the inter-Cloud Bridge argues for debris at distances around 40-70 kpc from us (cf. Figure 11 of Gardiner et al. 1994). When the debris is at the back of the LMC the source density will be much lower (by a factor $\mu_{db}/\mu_{LMC} \sim 0.1$ based on the density of the RR Lyraes in Sgr and LMC), but the lens density (hence the optical depth) increases by the same factor. As a result the microlensing event rate will be comparable for both cases, because the event rate is proportional to the product of the number density of stars in the debris and those in the LMC in both cases.

More rigorously, for a survey with N_s background source stars and N_f foreground point masses in the survey solid angle Ω , the expected number of events is given by

$$N_e = \epsilon N_s N_f \Omega_m / \Omega \quad (10)$$

where ϵ is the survey efficiency, and Ω_m is the solid angle significantly microlensed by a foreground moving point mass m during the survey, which is the angular area of the Einstein ring plus a rectangular area which is swept by the moving ring in the survey time T , so

$$\Omega_m = \pi \theta_E^2 + (2\theta_E)(|\vec{\omega}_{ls}| T), \quad (11)$$

where

$$2\theta_E = 4 \left[\frac{Gm}{c^2} \left(\frac{1}{D_l} - \frac{1}{D_s} \right) \right]^{\frac{1}{2}}, \quad (12)$$

is the angular diameter of the Einstein ring for significant microlensing amplification (0.34 magnitude) and

$$\vec{\omega}_{ls} = \frac{\vec{v}_{lo}}{D_l} - \frac{\vec{v}_{so}}{D_s} \quad (13)$$

is the relative proper motion rate of the source and the lens, and \vec{v}_{so} and \vec{v}_{lo} are the transverse velocities of the source and lens with respect to the observer. N_s and N_l are simply related to the surface mass densities Σ_s and Σ for the background sources (with mass m_s) and the foreground point masses multiplied by the areas,

$$N_s = \left(\frac{\Sigma_s}{m_s} \right) (\Omega D_s^2), \quad N_l = \left(\frac{\Sigma}{m} \right) (\Omega D_l^2). \quad (14)$$

As a result, in the limit that the survey time is much longer than any single event,

$$N_e \approx K T \Omega \Sigma_s \Sigma, \quad (15)$$

where

$$K = 4G^{\frac{1}{2}} c^{-1} m^{-\frac{1}{2}} m_s^{-1} D_s^{2.5} \sqrt{x(1-x)} |\vec{V}|, \quad (16)$$

and

$$\vec{V} = \vec{v}_{lo} - \vec{v}_{so} x. \quad (17)$$

Clearly N_e depends mainly on the product of the surface density in the background and in the foreground, so moving the debris from in front of the LMC to behind the LMC gives comparable number of events. For fixed x (say $x = 1/2 - 5/6$), the $D_s^{2.5}$ dependence in fact favors a far away source by a factor $(D_s/D_{LMC})^{2.5} = x^{-2.5} = (1.6-5.7)$. However, the efficiency ϵ biases against faraway sources with perhaps $\epsilon \propto D_s^{2\beta}$ due to a detection limit (Kiraga and Paczyński 1994), so that $K \propto D_s^{2.5-2\beta}$ is insensitive to source distance if β is between 1 and 1.5. The efficiency also depends on the amount of dust in front of the source.

The number of observable sources behind the LMC is reduced to a factor $1/y \approx 1/3$ (Sahu 1994) of intrinsic value due to screen-like dust extinction. The number of observable LMC sources is reduced to a factor $(1 - 1/y)/\log y \approx 0.6$ due to self-extinction. The values of K in both cases are approximately the same within a factor of two, insensitive to the values of y and β . So the number of events expected for a background debris tail is roughly the same as for the foreground debris tail.[†]

4 LENS MASS FUNCTION AND EVENT TIME-SCALES

4.1 Lens mass function

The Einstein diameter crossing time (Paczynski 1986) as a function of the mass of the lens m , the lens's relative velocity transverse to the observer-source line of sight $|\vec{V}|$ and the effective distance D is given by

$$2t_E \equiv \frac{2\theta_E}{|\vec{\omega}_{ls}|} \quad (18)$$

$$\approx 34\text{d.} \left(\frac{m}{0.1M_\odot} \right)^{\frac{1}{2}} \left(\frac{D}{12\text{kpc}} \right)^{\frac{1}{2}} \left(\frac{|\vec{V}|}{300\text{km s}^{-1}} \right)^{-1} \quad (19)$$

where I have scaled the quantities with characteristic values.

The 6 events recently reported by the MACHO collaboration have $2 \times t_E = 34 - 114$ days if excluding one binary event and one low confidence event (Alcock et al. 1996c). If the lenses of the LMC events were in a foreground dwarf galaxy rather than in the isothermal MACHO halo, then the spread of the lens's distance and velocity will be negligibly small, so the range in the duration of observed events is purely due to the mass function of the lenses.

If the dwarf galaxy is behind the LMC, and acts as the source instead of the lens, then the distribution of the effective distance and relative velocity will still be narrow. In both cases the roughly factor of 3 range in the observed t_E translates to about a factor of 10 in the lens mass m . The actual median mass depends sensitively on the proper motion of the dwarf galaxy and somewhat on its distance; a mass range between $0.1M_\odot$ to $1M_\odot$ is certainly a plausible solution for some combinations of distances and velocities.

4.2 Tidal debris

Most likely either the lenses or the sources are part of the tidal debris in the Magellanic great circle. They could be in the form a grand smooth tidal tail or several smaller tidal tails from disrupted dwarf galaxies in the plane. In all these cases several observable properties can be predicted.

The tidal debris has a transverse velocity proportional to that of the center of mass of the Magellanic Clouds

$$\vec{v}_{td} = x_{td}^{-1} \vec{v}_{LMC}, \quad (20)$$

[†] An effect left out here is that ϵ is also a function of amount of source blending, which is important for crowded fields in the LMC

because they share the same great circle orbit, hence have the same specific angular momentum; I have neglected the small offset of the Sun from the Galactic center and put the LMC at the center of mass of the Magellanic Clouds. The LMC has a proper motion of 1.2mas yr^{-1} (Jones, Klemola, Lin 1994), which translates to a Galactocentric transverse velocity $|\vec{v}_{LMC}| \approx 200\text{kms}^{-1}$ in direction leading the Magellanic Stream. So the relative proper motion between the tidal debris and the LMC is

$$\vec{\omega} = (1 - x_{td}^{-2}) \vec{\omega}_{LMC}, \quad \vec{\omega}_{LMC} = \frac{\vec{v}_{LMC}}{D_{LMC}}, \quad (21)$$

where I have left out the parallax due to the Sun's motion. So when peculiar motions of stars in the Magellanic Clouds and tidal debris are small compared to $\vec{\omega}$, then the model predicts that the lens-source proper motion vector $\vec{\omega}_{ls}$ will be approximately $\vec{\omega}$, which is parallel to the great circle of the Magellanic Stream, with an amplitude

$$|\vec{\omega}_{ls}| \approx |\vec{\omega}| \approx |\vec{\omega}_{LMC}| |1 - x_{td}^{-2}|. \quad (22)$$

The prediction can be compared with parallax measurements for individual microlensing events, which can determine the amplitude and direction of the reduced velocity $\vec{V}/(1 - x)$ (Gould 1994). The amplitude is predicted to be $|\vec{\omega}_{ls}| D_s x / (1 - x) \approx 200\text{kms}^{-1} (1 + x_{td}^{-1})$. However, the prediction is subject to large uncertainty when the tidal debris is very close to the LMC, x_{td} between $0.9 - 1.1$, so that the systematic velocity between the debris and the LMC is comparable to that of the rotation velocity of the LMC stars ($\sim 70\text{ km/s}$). When the debris tail is thick, the predicted amplitude (not direction) also varies for each event with the detailed location (x_{td}) of the lens or source.

The event time scale can also be predicted given a detailed kinematic model. In the current simple kinematic model t_E is a function of x_{td} .

$$2t_E \approx 34\text{d.} \left(\frac{m}{0.1M_\odot} \right)^{\frac{1}{2}} g(x_{td}) \quad (23)$$

where

$$g(x_{td}) = \left(\frac{|\vec{\omega}_{ls}|}{1.2\text{mas yr}^{-1}} \right)^{-1} \sqrt{\frac{1 - \text{Min}[x_{td}, x_{td}^{-1}]}{0.25}}. \quad (24)$$

For typical foreground debris distances x_{td} from $2/3$ to $4/5$, $g(x_{td})$ is between 2 to 2.5 ; for typical background debris distances x_{td}^{-1} from $2/3$ to $4/5$, $g(x_{td})$ is between 0.9 to 1.6 . So in both cases, a typical lens mass (in the foreground debris or in the LMC) of $0.1M_\odot$ is roughly consistent with the observed events.

With the increasing number of events, and a self-consistent N-body simulation of the infall of the Magellanic Clouds, which could predict the lens and source kinematics, it would be possible to test whether the derived lens mass function is consistent the luminosity function of the Large or Small Cloud. *If the lenses were from stars liberated from the Large or Small Clouds, they should have the same mass function as their parent galaxies.*

Bennett et al. (1996) found a caustic crossing binary event in the MACHO LMC data. Assuming the caustics are resolved by the finite size of a late A-type source star near the LMC disc, they derive an extremely low lens-source relative proper motion speed ($\sim 20\text{ km/s}$). Such small relative velocity is very unlikely for a halo lens, but is possible if

either the source or the binary lens is from the tidal debris within 2.5 kpc to the LMC, $|1 - x_{td}| < 0.05$. In this case the relative systematic velocity between the debris and the LMC is low, ≤ 30 km/s, so the velocity dispersion (~ 20 km/s) of the LMC stars becomes important, which can reduce the lens-source speed to the observed value.

This explanation is also consistent with most of the observed events being from the tidal debris. Caustic crossing binary events are intrinsically rare, in fact less than a handful of caustic crossing binary events are found among more than one hundred events towards the Galactic bulge and the LMC. Bennett et al. found that it is difficult to explain all LMC events by the LMC self-lensing due to its low optical depth if the LMC disc is close to face-on (Gould 1995). But the observed 5-10 ordinary events and one caustic event is consistent with them being from sources or lenses in the tidal debris with a few kpc of the LMC. It would be interesting to see whether we will detect another such LMC comoving binary event when the number of LMC events doubles in the coming year.

5 POSSIBLE INTERPRETATIONS OF THE LMC LENSING EVENTS

There are a few simple interpretations of the non-zero but low optical depth towards the LMC.

(1) The dark halo is in distributed particles, and either (a) events due to self-lensing of LMC stars (Sahu 1994) are underestimated, or (b) background events due to a non-uniform stellar halo of the Galaxy are underestimated.

(2) There are numerous MACHOs in the halo, but either (a) the entire halo is made of MACHOs but with a density distribution varying markedly with line-of-sight directions, or (b) the halo indeed has a smooth r^{-2} distribution but with a constant mix of white dwarf like objects and weakly interacting massive particles (Alcock et al. 1996c).

Even a small mass fluctuation in the halo can greatly influence conclusions on the amount of massive compact objects in the halo. The projected mass density of stars in a dwarf galaxy, $\sim (2Y) \sim 20 M_{\odot} pc^{-2}$, is comparable to an isothermal halo, $\sim (V_{cir}^2 f_{MACHO}) (4\pi Gr)^{-1} \sim (100 f_{MACHO}) \sim 30 M_{\odot} pc^{-2}$, where f_{MACHO} is the fraction of the halo mass in MACHOs, and $r \sim 8$ kpc is the typical distance to the MACHOs, and $V_{cir} \sim 220$ km s $^{-1}$ is the amplitude of the gas rotation curve of the Galaxy. So faint stars in a $10^{8-9} M_{\odot}$ satellite galaxy can produce an optical depth (cf. eq. 7 and 8) comparable to that of a $2 \times 10^{11} M_{\odot}$ isothermal halo of WDs: $\tau_{dh} \sim f_{MACHO} \frac{V_{cir}^2}{c^2} \sim 0.15 \times 10^{-6}$ (Alcock et al. 1996a).

If one relaxes the model assumption to allow MACHOs (such as stellar remnants, brown dwarfs and Jupiter-mass objects) to dominate in both dwarf galaxies and the Galactic halo (as in case 2a), then the optical depth of the dwarf can increase by one order of magnitude $\tau_{dg} \sim \tau_{obs} \frac{M/L}{10 M_{\odot}/L_{\odot}} \sim 10 \tau_{obs}$ (cf. eq. 7 and 8), given the high $M/L \sim 100$ of dwarfs. Now suppose the MACHO-dominated dwarf galaxies which come into merge with the halo has a mass spectrum $\frac{dN}{d \log M} = N_0 (M/10^{10} M_{\odot})^{-1}$ with mass M from $3 \times 10^6 - 10^{10} M_{\odot}$, and they are now in various stage of disruption in the halo; some cover as much as 0.2% of the full sky solid angle per tidal

tail. Looking through this clumpy halo the optical depth (and to some extent the event duration) will be a wildly oscillating function of line-of-sight directions on scales of several degrees. In this picture one would need to observe at least several directions to estimate the average optical depth. One can not argue any single line of sight, say the LMC, is typical or not. It becomes problematic to constrain the spatial distribution and spectrum of MACHOs with the observed microlensing events in the LMC direction.

The LMC self-lensing (Sahu 1994) is efficient when the “depth” of the LMC is big. In this aspect the SMC has a more favorable geometry than the LMC, the former being a very elongated bar pointing close to us with a depth about 10 kpc (Caldwell & Coulson 1986). The event rate is only limited by the source density, which is much lower than the LMC. I expect comparable number of events from SMC self-lensing and lensing by halo dwarf galaxy or MACHOs. I also estimate comparable event rate (roughly one event per year for MACHO experiment) coming from LMC self-lensing, SMC self-lensing, and the lensing of Sgr by foreground bulge stars.

It is possible to test whether the lenses are on the LMC. If sources are the far side of the LMC or behind the LMC, one expects the lensed sources to be systematically shifted towards fainter and redder part of the CM diagram than the average LMC stars in the survey due to distance and extinction. The event rate is a function of line-of-sight position, proportional to the surface density of foreground lenses and that of background sources (cf. eq. 15). The gradient of the surface density of an isothermal MACHO halo or tidal tails is generally shallow, the projected density of the LMC is peaked to its central bar. Color-Magnitude diagram and spatial information of the lensed sources can be used to test various distributions of the sources and lenses. The event distribution (spatial, time, color-magnitude) to the SMC and the M31 are also indicators to differentiate the models.

Event rate towards the M31 depends on the covering factor of any tidal debris in its halo and any chance intervening tidal material in our Galactic halo. No strong conclusions can yet be drawn from the current handful of events (Alcock et al. 1996c, Ansari et al. 1996, Crofts & Tomaney 1996).

6 SEARCHING FOR FOSSILS OF PAST MERGERS

The north and south Galactic poles are two good directions to search for tidal material because polar orbits have zero angular momentum with respect to the rotation axis of the Galactic disc, and are likely populated by infalling satellites. Three postulated streams, the Magellanic-Draco-Ursa Minor stream, the Fornax-Leo(I & II)-Sculptor-Sextans stream, and the Sgr stream are all on polar great circles. Stars in a stream are distinguishable from field stars by their narrow distribution in distance modulus, radial velocity, and proper motion.

The studies should combine photometric surveys with kinematics. Dwarf galaxies and the Magellanic Clouds are massive enough to contain globular clusters and planetary nebulae, and they are also rich in metal poor RR Lyraes and carbon stars. All these have played important roles in discov-

ering the Sgr galaxy. Sky positions and sometimes distances of these luminous tracers can be used to map the streams in the halo. Several methods for interpreting the data have been developed by exploiting the fact that the tidal tails at large radius in the halo nearly trace great circles (Lynden-Bell and Lynden-Bell 1995, Johnston et al. 1996).

Since pure photometric surveys are generally inconclusive, kinematic confirmation is crucial. The tangential proper motion of a stream generally has a large positive or negative value ($\sim \pm 200$ km/s) as the stars in a stream are bunched in phase as well as in orbit; Majewski, Munn, Hawley (1994) have applied this method to identify a moving group towards the north Galactic pole. When an extended region is studied, a sinusoidal variation of the radial velocity with the angular position along the orbit is also detectable (Kunkel 1979, Johnston et al. 1996). Such distributions are markedly different from that of a pressure-supported stellar halo.

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